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LASER PROPAGATION CODE STUDY

by

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A number of laser propagation codes have been assessed as to their suitability for modeling Army High Energy Laser (HEL) weapons used in an anti-sensor mode. We identify a number of areas in which systems analysis HEL codes are deficient. Most notably, available HEL scaling law codes model the laser aperture as circular, possibly with a fixed (e.g. 10%) obscuration. However, most HELs have rectagular apertures with up to 30% obscuration. We present a beam-quality/aperture shape scaling relation which can be useful when applying these codes to realistic designs for HELs.

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LASER PROPAGATION CODE STUDY

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Edward B. Rockower

I. INTRODUCTION and SUMMARY

During the course of this study a number of laser propagation codes have been assessed as to their suitability for modeling Army High Energy Laser weapons used in an anti-sensor mode. Because the Army battlefield scenario requires nonlinear laser beam propagation through turbulent atmospheric conditions, including smoke and dust, these aspects have required (and received) the greatest modeling effort (see, e.g. [1]). However, other important features of High Energy Laser weapons are the rectangular aperture and large (possibly up to 50%) central obscuration necessitated by the unstable resonator designs common to most high energy lasers.

The adequacy of the codes in modeling these, and other, aspects of operational lasers has required validation. This report will identify some apparent problems with current modeling in the codes, propose an interim "fix", where possible, and outline an approach to recommended further work, based on our study of the issues identified.

Two major categories of code have been investigated in our study:

1. Fundamental wave optics codes; these codes start from the basic microscopic laws of E-M radiation and implement various phenomenological models of the atmospheric turbulence and particulates. A number of schemes for numerically integrating the resulting approximations to the coupled partial differential equations have been mechanized on computer (see Table I for a listing of these and other codes).

2. Moderate accuracy system-level scaling law codes; these codes start from phenomenological and analytical approximations to the E-M wave equations, and attempt to represent the details of propagation through the atmosphere with a few parameters (e.g. a phase integral) based on integrated properties of the atmospheric conditions, light intensity, wave length, etc. These codes are based on experimentally and numerically (from the fundamental wave optics codes) derived data bases.

A large portion of the analysis reported here is relative to two baseline codes, one from each of the above categories. In the first category is the 4-D code developed by Joe Fleck and Jim Morris at Lawrence Livermore National Laboratory[2]. In the second, scaling law, category is the BRLPRO code developed by Harold Breaux of the Ballistic Research Laboratory, a version of which is contained in the HELAWS code which models Army high energy anti-sensor laser weapons[3]. During the course of this

study, this code has been modified slightly while installing it on the Naval Postgraduate School (NPS) IBM 3033 computer system in order to make it compatible with the CMS operating system and IBM Fortran 77.

A relatively large number of computer codes have been developed at various institutions in order to model high energy laser propagation. Unfortunately, the capabilities and limitations of these codes are not always immediately apparent from a perusal of their documentation. Some of the limitations are common to all of the codes; e.g., the code may only handle circular laser apertures. This limitation has not stopped the application of the codes outside their range of validity. Other limitations are those, such as assuming a vacuum in which the laser propagates, which clearly preclude use of such codes other than in a Space Warfare scenario. In order to attempt to make a preliminary assessment of what s available we have relied heavily on telephone conversations with engineers and analysts at various institutions regarding their codes. In addition, significant source of information has been a survey of 26 existing wave-optics, scaling law, and simplified geometric laser propagation codes (see Table 1) carried out by Dr. James P. Reilly and co-workers at W. J. Schafer Associates, Inc. in 1979 [4].

TABLE 1: PROPAGATION CODES

CODE	TYPE*	DEVELOPED BY	EXERCISED BY
APM	SC	HEL Systems Project Office	Army
BREAUX	SC	Ballistics Research Laboratory	Army
COMBO	SC	Air Force Weapons Laboratory	Air Force
EAPM	SC	Charles Stark Draper Laboraory	Charles Stark Draper Lab.
ESP III	SC	United Technologies Research Center	Air Force
ESP IIIA	SC	United Technologies Research Center	Air Force/Army
ESP IV	SC	United Technologies Research Center	Air Force
GEBHARDT	SC	Science Applications, Inc.	Army
GUTS	SC	Air Force Weapons Laboratory	Air Force
HELP (PROPMD)	WO	Air Force Weapons Laboratory	Air Force
JW/4-D	WO	Far Field, Incorporated	Far Field, Incorporated
LASE	SL	Science Applications, Inc.	Navy
LASNEX	GO	Lawrence Livermore Laboratory	Lawrence Livermore Lab.
LL/SL	SL	Lincoln Laboratory	Lincoln Laboratory
LL/WO	WO	Lincoln Laboratory	Lincoln Laboratory
LLL/4D	WO	Lawrence Livermore Laboratory	Lawrence Livermore Lab.
MPLAW	SL	Naval Research Laboratory	Navy
NOLEC	SC	Naval Ordnance Laboratory	Navy
NRL/CHM	WO	Naval Research Lab/SAI	Navy
NRL/JL	SC	Naval Research Laboratory	Navy
PHILLIPS/SL	SL	Science Applications, Inc.	Navy
PSM	WO	Charles Stark Draper Laboratory	CSDL
SAICOM	SC	Science Applications, Inc.	Navy
SSPARAMA	WO	Naval Research Laboratory	Navy
UTRC/WO	WO	United Technologies Research Center	United Technologies Resear Center
ZAPM	SC	W. J. Schafer Associates, Inc.	W. J. Schafer Associates,

* WO - Wave Optics Code SC - Simplified Code

SL - Scaling Law GO - Geometric Optics/Hydrodynamic Code

II. APERTURE SHAPE PROBLEMS

In conversations with analysts and programmers regarding their codes and in study of the documention on other codes, where available, it is apparent that virtually all non-wave-optics codes force the user to model his laser as having a circular beam profile at the laser aperture. As mentioned above, most high energy chemical lasers have rectangular apertures. In addition, there is often a central or non-central obscuration of the beam profile at the laser aperture, caused by one mirror of the unstable resonator configuration. In attempting to exercise such a propagation code to simulate rectangular aperture lasers, it is reasonable to try to maintain both the same output power as well as output beam intensity as for the real laser. If the former condition is met, then the latter is equivalent to requiring that the area of the circular aperture (with or without a central obscuration) be the same as for the real laser.

The following analysis is an attempt to estimate the seriousness of the limitation to circular apertures and lead to a proposal for an interim fix. Finally, we suggest a possible course of further work on this problem.

An asymptotic approximation formula for estimating the fraction of encircled energy within a given radius has been

derived for imaging systems with oddly shaped apertures[5]. Modulation Transfer Function (MTF) techniques were applied to a uniformly illuminated aperture having arbitrary shape and obscurations, resulting in the following formula, valid for asymptotically large values of r,

$$E(r) = 1 - \lambda f R/(2\pi^2 r)$$

where λ = laser wavelength

f = effective focal length

r = radial dimension in the focal plane

R = HEL aperture perimeter-to-area ration

E = normalized encircled energy, i.e. the fraction of the energy transmitted by the aperture that falls within a circle of radius r about the geometrical focal point.

The main feature of this result for our purposes is that, apart from the laser wavelength and system focal distance, the fraction of encircled energy depends only on the ratio R/r, where R is the ratio (perimeter/area) for the imaging system aperture, and r is the radial dimension in the focal plane within which one wishes to determine the fraction of total energy. Asymptotically, the fraction of encircled energy is independent of details of the shape, apart from the value of R. It is assumed that the laser beam propagates in a linear medium,

with no effects of atmospheric fluctuations, wind, etc. and that the laser aperture is uniformly illuminated.

Analyzing this result, we conclude that, at least for the restricted conditions under which it was derived, the radius (r) encircling a given fraction of energy increases linearly with R. In other words, a beam from an aperture with double the value of R will, asymptotically, spread twice as much, from diffraction. Hence, again subject to the limitations of applicability, the spread of a beam in free space propagation will be proportional to the ratio of the lasers perimeter to its area.

There is a somewhat similar effect that is a well known consequence of imperfections of laser wavefront quality at the point where the beam leaves the laser aperture. Whatever the cause of the degraded beam quality (phase front distortions), whether from inhomogeneities in the lasing medium, mirror or lens imperfections, etc., the effects on beam propagation are represented with a parameter known as the "beam quality" (M). The value of M is always greater than or equal to 1 and is known as "times diffraction limited"; i.e., the beam spread is M times the diffraction limited rate of beam divergence (proportional to lambda/D). Comparing the two results for beam spread, we identify a possible method of compensating, at least partially, for rectangular apertures and various sizes and types (e.g. non-central) of obscuration. Our conclusion is, for free space

propagation, that the asymptotic spread of lasers emanating from two apertures having the same value of the product $M*R$ will be the same. Hence, a better approximation to a rectangular aperture, possibly with a central obscuration, than just finding the circular aperture with the same total area, is to also change the value of beam quality, M, so that the relation

$$MR = M'R'$$

is preserved.

For example, we can model a circular aperture with a central obscuration with another circular aperture of the same area, output power, and with beam quality given by $M' = M(R/R')$. These two requirements lead to,

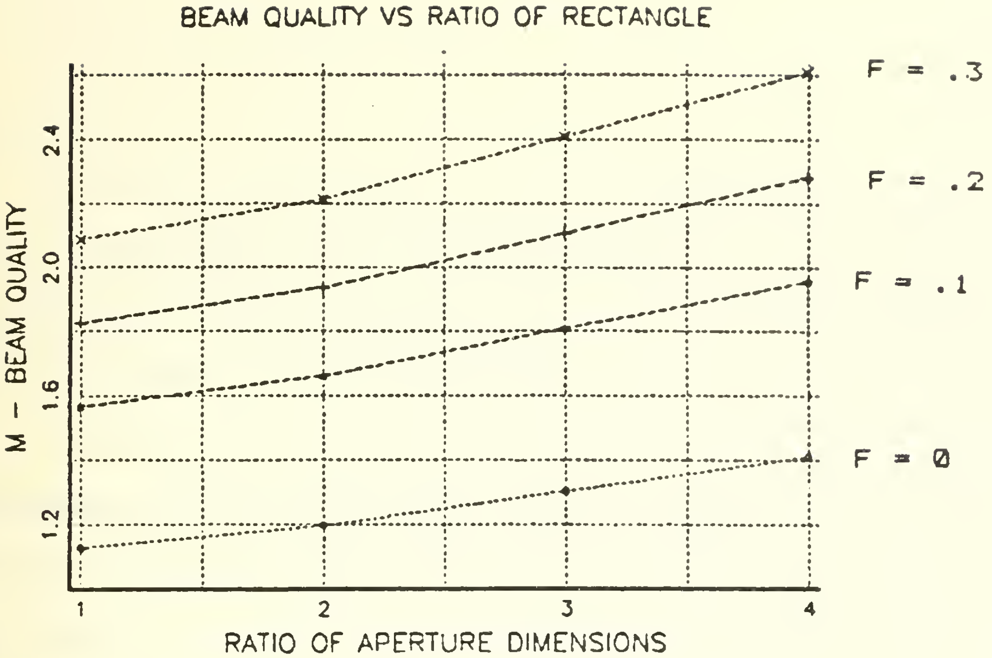
<u>Circular Apertures</u>:

$$M' = M\,(1 + \sqrt{F})/\sqrt{(1 - F)}$$

$$D' = D\,\sqrt{(1 - F)}$$

where F is the fraction obscuration.

We have also derived similar equations for rectangular apertures with and without obscurations. The results for the latter are presented in graphical form in Figure 1. Each curve in that



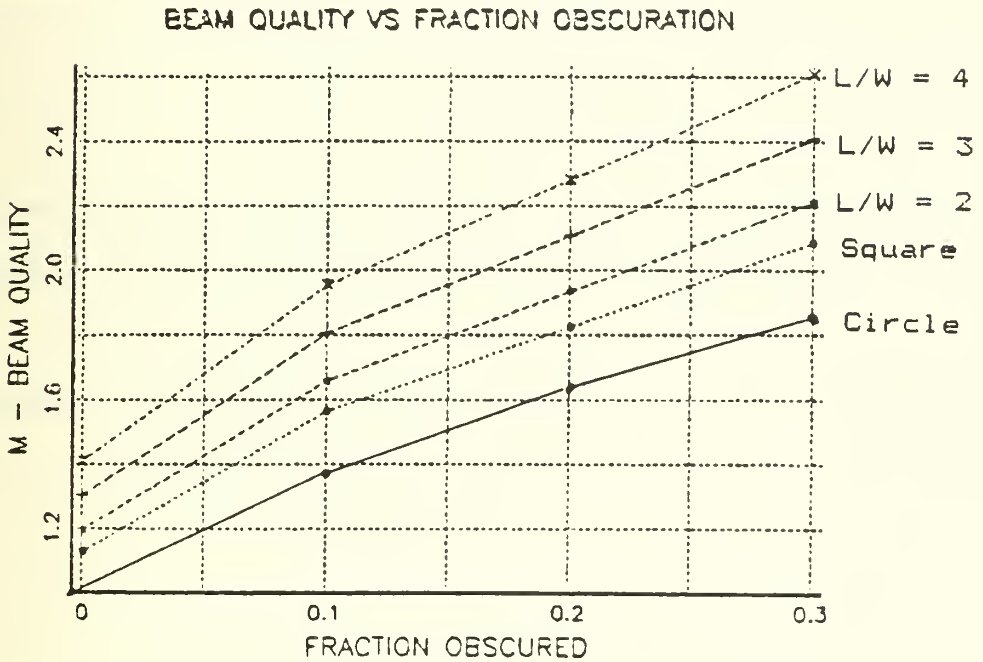


Figure 1. Beam quality as a function of Length/Width ratio (L/W) and Fraction obscuration (F).

figure gives the beam quality of an "equivalent" uniform circular aperture with the same area as the rectangular aperture whose length to width ratio (L/W) is shown to the right of the curve. The curve for a circular aperture with obscuration F is also shown.

It remains to determine whether the above results have any relevance or usefulness for nonlinear laser propagation within a turbulent atmosphere.

In order to estimate the magnitude of the problem and to determine whether the similarity transformation derived above may be useful we have exercised the HELAWS code (containing BRLPRO) with the following specific questions in mind:

1) How adequate is the remedy of simply representing a rectangular aperture by using a circular one of equal area?

2) How adequate is it to represent a centrally obscured aperture by means of a circular aperture with the same overall area, power, and (therefore) intensity?

3) Given that we would like to try to represent different aperture shapes and obscurations with our similarity transformation, how good a fix can be obtained in the presence of <u>linear</u> atmospheric effects such as turbulence and wind?

4) How good is our transformation in face of nonlinear effects, i.e. thermal blooming?

5) How can the existing codes be improved, possibly with an extension of the similarity transformation, or otherwise.

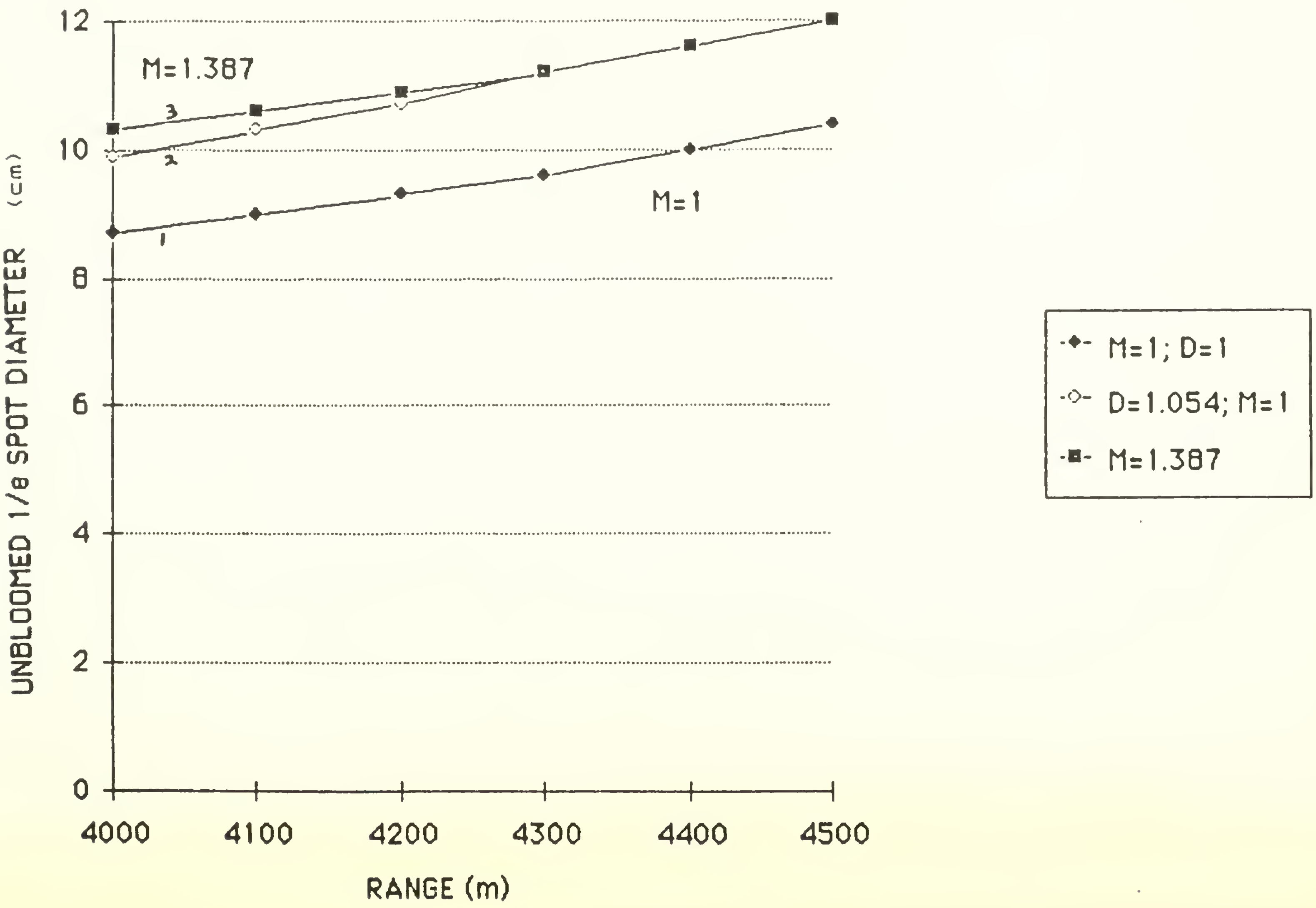
With reference to the above questions, we now look at the following 3 figures. The data were generated with the output from HELAWS, using variations of the base case parameters shown in Table 2.

On each of the figures, curve (1) represents the results for a reference uniformly illuminated circular aperture of diameter of one meter, beam quality equal to one. Curve (2) presents the results for a uniformly illuminated circular aperture with a 10% central obscuration but with the same area and beam quality (i.e. M = 1) as the base case. Since F = .1, one of our previous formulae yields D_e = 1.054*D. Finally, curve (3) presents the results for a uniformly illuminated circular aperture (no obscuration), equal area as before, but with beam quality calculated from our formula to give the same free space asymptotic beam spread as the aperture with 10% obscuration (i.e. curve 2). Our formula presented above yields M_e = 1.38 . This can also, approximately, be read off of figure 4 which shows the

TABLE 2: HELAWS CODE INPUT PARAMETERS

LASER PARAMETERS	
LASER CODE	R1-B3
OPERATING MODE	RP
WAVELENGTH	10.6 MICRONS
BEAM QUALITY (TIMES DIFFRACTION LIMITED)	1.39 X DL
APERTURE MIRROR DIAMETER	1.000 M
TOTAL SYS. JITTER (1 SIGMA)	10.0 URAD
VARIABLE FOCAL RANGE	EQUAL TO TGT RANGE
AIMPOINT OFFSET: X COORDINATE	0.00 M
AIMPOINT OFFSET: Y COORDINATE	0.00 M
STD. DEV. OF AIM BIAS ERROR (1 SIGMA)	5.0 URAD
ENERGY PER PULSE	10.0 KJ
PULSE REPETITION RATE	5.0 P/SEC
PULSE DURATION (OR WIDTH)	20.0 USEC
ATMOSPHERIC PARAMETERS	
SCENARIO LOCATION	EUROPE
SCENARIO LONGITUDE	9.0 DEG
SCENARIO LATITUDE	50.0 DEG
TIME OF YEAR	OCT
TIME OF DAY	10.00 HRS
VISIBILITY RANGE	7.00 KM
AMBIENT TEMPERATURE	10.0 DEG C
RELATIVE HUMIDITY	85.0
ATMOSPHERIC PRESSURE	985.0 MB
TURBULENCE LEVEL	MODERATE
REFRACTIVE INDEX STRUCTURE CONST (AT 1M)	8.40E-14 M**(-2/3)
SCALING OPTIONS EMPLOYED	YES
MAGNITUDE OF WIND VELOCITY AT REF HEIGHT	1.0 M/S
REFERENCE HEIGHT FOR WIND VEL ALTITUDE SCALING	1.0 M
WIND DIRECTION ANGLE (TO SOUTH=0 DEG, TO WEST=90 DEG)	220. M
ENGAGEMENT PARAMETERS	
INITIAL TARGET RANGE	4000. M
MAXIMUM TARGET RANGE	4500. M
RANGE INCREMENT	100. M
ALTITUDE OF LASER APERTURE	2.8 M
ALTITUDE OF TARGET	1.5 M

LASER PROPAGATION CODE STUDY



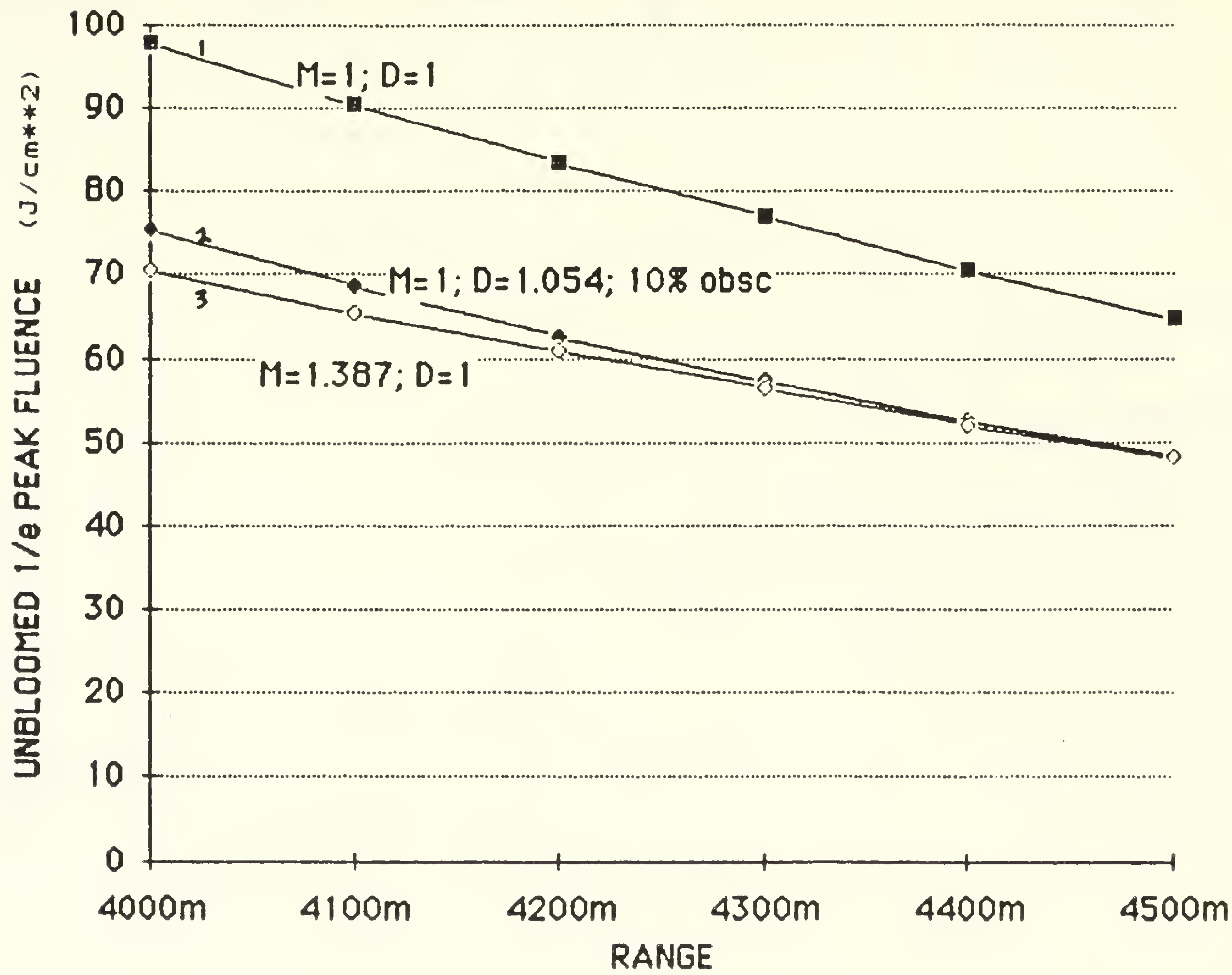
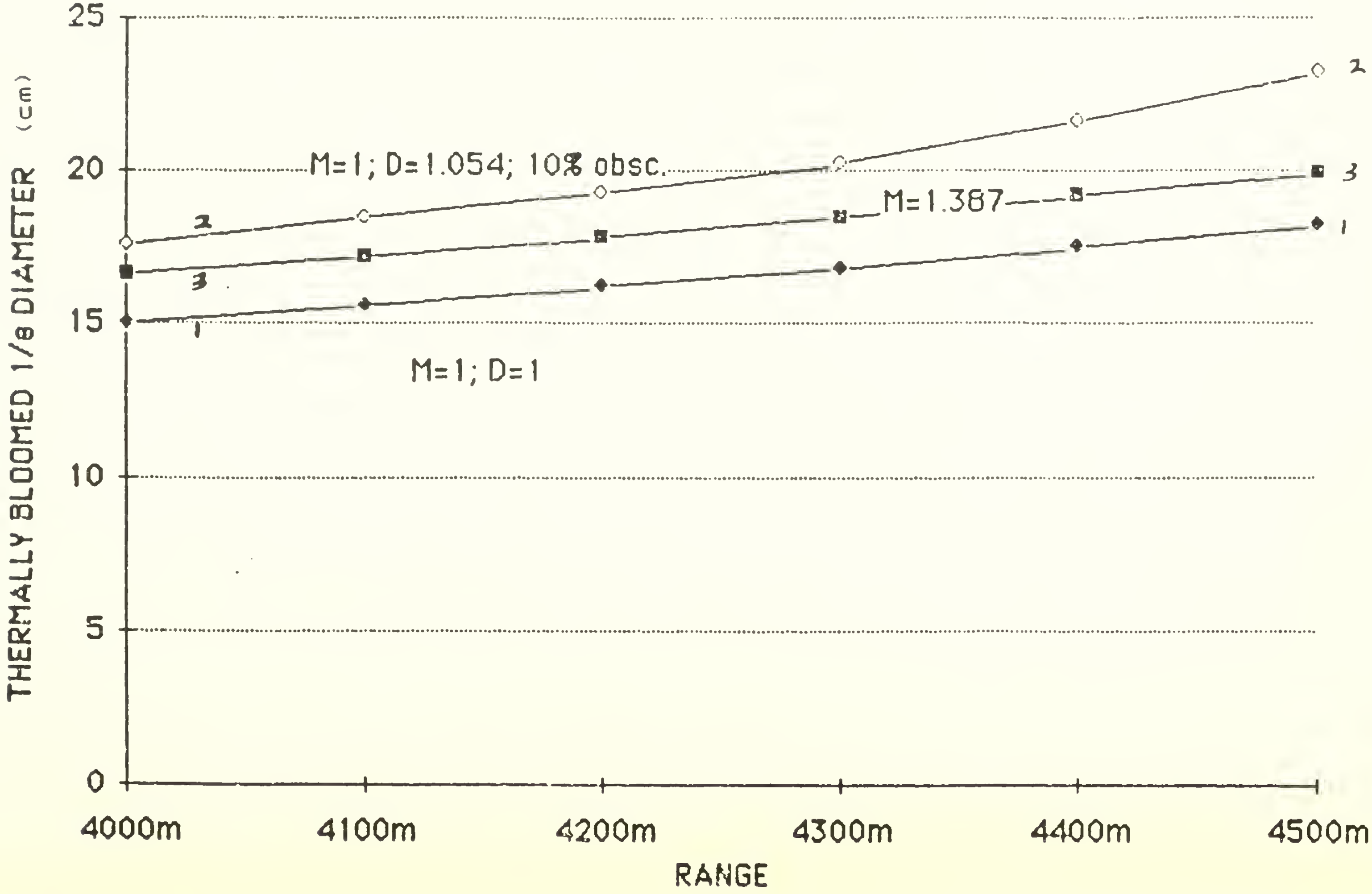


Figure 3. Unbloomed peak fluence vs. range.

LASER PROPAGATION CODE STUDY



required beam quality of an equivalent circular aperture laser for various shapes and values of F.

First, let's look at figures 2 and 3, showing the unbloomed 1/e spot diameter and unbloomed 1/e peak fluence, respectively. Comparing curves (1) and (2) shows that simply trying to represent a 10% obscuration with a circular aperture of equal area would lead to gross errors. We now appeal to the encircled energy theorem and note that it is easy to show that there is a rectangular aperture (L/W approx. = 1.9) with the same area and value of R as the 10% obscured circular aperture. Hence, by the encircled energy theorem the rectangle will have the same asymptotic beam spread as will the obscured circle. Clearly, if one tries to represent such a rectangle with the unobscured circular aperture (curve 1), then the same gross errors will result, even without thermal blooming (there's certainly no reason to believe that the nonlinear thermal blooming will help matters here).

Still looking at figures 2 and 3, now note curve (3) which corresponds to an unobscured circular aperture with the same area as the other cases but with beam quality M set by the requirement that M*R matches that of the 10% obscuration case. We see that the match is excellent beyond about 4300 meters. Apparently this range defines the beginning of the asymptotic region for the conditions of these computer runs. Two things

are worth noting here: 1) the M*R = const. similarity relation appears to work quite well, becoming better as the range increases, lending credence to our reasoning regarding the scaling of diffraction beam spreading, whether arising from M or from R, and 2) remarkably, our result works well even for propagation in the atmosphere, with its turbulence fluctuations(described as moderate for this case) and wind (but without thermal blooming). Hence, the similarity relation holds even beyond the range of validity implied by the conditions of its derivation.

Consulting figure 4, in which the thermallly bloomed the spot diameter is plotted, we see that adding the beam quality factor to the equal area circular aperture (curve 3) gets us only a little over half way to the 10% obscured aperture results (curve 2). Hence, when the nonlinear effects of thermal blooming are considered, the central obscuration is not so easily compensated for by our beam quality similarity relation. However, the code already handles the 10% obscuration case, and we are only looking for a means of extending the range of existing propagation codes to include larger obscurations and rectangular apertures. Clearly, using the principle of constant M*R [illegible] is part way there. Hence, a possible approach is to generalize and extend the beam quality vs. R scaling relation (or similarity relation) to the nonlinear region by a) fitting curves to

existing code output, and/or b) having identified the extent of the problem and a possible direction for a phenomenological fix, carry out studies with existing wave-optics codes on rectangular apertures and larger obscurations to obtain the applicable scaling laws. Possibly some generalization of R*M = const. which also accounts for beam power, e.g. R*M = f(I) where I is the beam intensity, will prove adequate.

III. AIM BIAS AND DISPERSION

A number of the codes surveyed allow at most two options regarding focus of the laser beam. Either the user must assume exact focus on the target, or the focus is at infinity. Whether this is justified or not should be determined for the specific, realistic pointing and tracking, and laser focusing systems being planned for. It is not difficult to show with some very simple calculations that a range error, whether bias (constant from pulse to pulse) or dispersion can lead to appreciable spreading of the laser energy at the true target range. No conclusion can be drawn without specific predictions for the focusing system parameters.

With regard to bias of the laser system, a straightforward analysis of the inputs and outputs from the HELAWS code indicate that there will be cases in which the low frequency atmospheric

turbulence and wind-induced aim bias, which, along with the postulated levels of laser system pointing bias will dominate the dispersion errors. For those cases with high levels of low frequency atmospheric turbulence and/or system aim bias, it may be that the optimal firing will require either some type of pattern-firing of laser pulses or possibly an added dispersion (shot gun effect) to compensate.

IV. CONCLUSIONS AND RECOMMENDATIONS

Based on our survey of a number of high energy laser propagation codes, it would appear that none are highly precise tools for evaluating Army laser weapons systems operating in realistic environments. That this may be true is not surprising for the wave optics codes which were generally designed to be highly precise codes, valuable for baselining the more phenomenological scaling codes intended for systems level studies. However, they were usually not designed to include the range of effects in an efficient computational form to be used in systems studies.

However, consider the statement in [3] vol. I p. I-8, "Real HEL beams may have rectangular cross-sections with non-central or non-circular obscurations with greater (or less) than 10%.

obscuration....... However, given the current primitive state of HEL weapon development and the intended systems analysis applications of HELAWS, the BRLPRO assumptions for the beam characteristics are sufficiently accurate." This may seriously underestimate the errors in approximating a rectangular aperture or one with larger than 10% obscuration (or both) with a suitably chosen circular aperture, possibly with 10% obscuration. We feel that our discussion in section II of this report is sufficient grounds to question the above quote.

Hence, it may be advisable to consider some of the suggestions outlined in section II, above, regarding modifications of present codes to more realistically handle rectangular apertures and larger obscurations. Ultimately there must be some validation either with a wave-optics code (such as the Livermore 4-D code, the NRL SSPARAMA code, etc) or with experiments on existing high energy laser systems.

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